# The radial distribution of type Ia supernovae in early-type galaxies: implications for progenitor scenarios

Francisco Förster[1]⋆ and Kevin Schawinski[1]†

[1] *Dept. of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, United Kingdom*

**ABSTRACT**

We study the radial distribution of supernova Ia (SNe Ia) in morphologically selected early–type host galaxies from the *Sloan Digital Sky Survey* (SDSS) and discuss its implications for the progenitor systems of SNe Ia. While new observations of early-type galaxies suggest that they contain small fractions of young stellar populations, they are also the most likely hosts for long time delay SNe Ia. We find that there is no statistically significant difference between the radial distribution of SNe Ia and the light profile of their early–type host galaxies, which are dominated by old, metal-rich stellar populations. This confirms the commonly accepted idea that some SN Ia progenitors have time delays of the order of several Gyr.

**Key words:** supernovae: general, chemical: general.

## 1 INTRODUCTION

Type Ia supernovae (SNe Ia) have been extensively used as distance indicators for cosmology (see e.g. Riess et al. 1998; Perlmutter et al. 1999) using the *empirical* Phillips relation (Phillips 1993) and related methods. They are also important for understanding galaxy evolution, affecting the chemistry and energy budget of their hosts, and the star formation and metallicity evolution of the Universe. Uncertainties in both the progenitor scenarios and the explosion mechanism (for a review see Hillebrandt & Niemeyer 2000) prevent us from having a convincing physical picture that justifies their use as *standardisable* candles at high redshift and is able to reproduce their observed diversity in the local Universe.

### 1.1 The SN Ia time delay distribution

Linking SN Ia progenitor scenarios with cosmology, galaxy evolution and the cosmic star formation history requires information on the time between their formation and explosion, or time delay distribution. Thermonuclear explosions seem to originate in white dwarf stars (WDs), with main sequence (MS) lifetimes ranging from $\sim 30$ Myr to several billion years, thus the minimum time delay must be of the order of $\sim 30$ Myr. To narrow the constraints details of possible **progenitor systems** need to be used.

⋆ fxf@astro.ox.ac.uk
† kevins@astro.ox.ac.uk

Most proposed progenitor scenarios involve mass transfer on to a CO WD that reaches the Chandrasekhar limit in a binary system. In these scenarios the WD grows through either the expansion and Roche lobe overflow of an evolved companion (*single degenerate [SD] scenarios*), or the slow release of gravitational waves, orbital shrinking, Roche lobe overflow and merging of a compact double WD system (*double-degenerate [DD] scenarios*).

For the SD scenario it has been suggested that only systems that can transfer enough mass under a critical rate can bring the WD star to the Chandrasekhar limit (Nomoto & Kondo 1991). In binary population synthesis (BPS) simulations most of the WDs that reach the Chandrasekhar mass accrete matter from a slightly evolved MS star, the so called CO WD + MS – SD scenario (Hachisu et al. 1999; Langer et al. 2000; Han & Podsiadlowski 2004). In this channel the mass of the companion determines both when accretion starts and the rate of accretion. As a consequence, the time-delay distribution of this channel seem to be relatively narrow, peaking at $\sim 670$ Myr and rapidly becoming negligible after $\sim 1.5$ Gyr.

Several Gyr time–delay progenitors can also be produced in the SD scenario when a relatively low mass red-giant (RG) star transfers matter on to a CO WD star, in the CO WD + RG – SD scenario (Hachisu & Nomoto 1996). This scenario appears to be supported by observational evidence (Patat et al. 2007), although its relative contribution is unclear (Han & Podsiadlowski 2004).

The characteristic time delay in the DD scenario (Iben & Tutukov 1984; Webbink 1984) is the coalescence time–scale of the binary system, which depends roughly on

the fourth power of the separation of the double-degenerate system (Shapiro & Teukolsky 1983). The time-delay distribution can be described by a low time-delay cutoff ($\sim$ $30 - 100$ Myr), an approximately power-law decline up to the age of the Universe and some secondary peaks depending on the details of the BPS simulation.

However, the expected accretion rates in the DD scenario are thought to be too big to lead to successful thermonuclear explosions, with most simulations leading to accretion-induced collapse (AIC) and the formation of compact objects instead (see Saio & Nomoto 1998, and references therein). Rotation or more sophisticated neutrino physics may give this channel a more significant role in the future (Yoon, Podsiadlowski, & Rosswog 2007).

Observationally, a comparison between the cosmic supernova rate and star formation history has led to indirect constraints on the time delay distribution (see e.g. Gal-Yam & Maoz 2004; Strolger et al. 2004; Hopkins & Beacom 2006), but uncertainties in both functional quantities seem unlikely to give constraints with the required accuracy to distinguish between different channels (Förster et al. 2006; Blanc & Greggio 2008).

A better probe for clues regarding the SN Ia time delay distribution might be to look at their individual host galaxies (see e.g. Mannucci et al. 2005; Sullivan et al. 2006; Prieto, Stanek, & Beacom 2008) and their galaxy environments (see e.g. Sharon et al. 2007). With this approach uncertainties in the star formation histories of individual galaxies can be better controlled if accurate stellar population reconstructions are used.

## 1.2   Early–type galaxies

The dominant stellar populations of early–type galaxies are old and must have formed in the high redshift universe (see Thomas et al. 2005, and references therein).

However, the GALEX UV space telescope has led to the discovery that a significant fraction of early–type galaxies in the low redshift universe formed a few percent of their stellar mass in the last Gyr (Yi et al. 2005; Schawinski et al. 2006; Kaviraj et al. 2007; Schawinski et al. 2007). These episodes of residual star formation are not apparent in the optical, but become prominent in the UV. This opens up the possibility that the SNe Ia observed in apparently passive early–type galaxies may be due to these small young populations and so might have short time delays.

The bulk stellar population of massive early-type galaxies follow a $r^{1/4}$ or de Vaucouleurs law (de Vaucouleurs 1948) and the dynamical relaxation time–scale of these systems is much higher than the age of the Universe (Binney & Tremaine 1987). High resolution H$\beta$ maps have been used to trace young stellar populations in early-type galaxies and they tend not to follow the typical de Vaucouleurs profile of their hosts (Sarzi et al. 2006; Kuntschner et al. 2006). Evidence for central molecular disks in early-type galaxies supports this idea (Lucero & Young 2007; Crocker et al. 2008).

If the radial distribution of SNe Ia follows the light of the bulk stellar population in early–type galaxies, then their progenitors must have an age of at least the minimum between the relaxation time–scale and the age of the bulk of the stellar population. We attempt to quantitatively test whether the radial distribution of SNe Ia follows a de Vaucouleurs law.

## 2   SAMPLE SELECTION

We create a sample of SN Ia early-type host galaxies by selecting all SNe Ia in the CfA list of supernovae[1] whose hosts have been covered by the Sloan Digital Sky Survey (SDSS, York et al. 2000; Stoughton et al. 2002). The SDSS is a survey of half the Northern Sky, providing us with photometry in the five optical filters $u,g,r,i$ and $z$ (Fukugita et al. 1996; Gunn et al. 1998). We use the current data release DR6 (Adelman-McCarthy et al. 2008).

We visually inspect every SN Ia host galaxy observed by SDSS and select only those with early-type morphology. Visual classification avoids the introduction of biases associated with proxies for morphology such as colour, concentration or structural parameters (Lintott et al. 2008). From the remaining galaxies we select those with half–light radii bigger than $2.4''$, or six pixels in the SDSS images. The final sample contained galaxies with a mean and median half–light radius of $17.6''$ and $12.9''$, or about 44 and 32 pixels, respectively. Their redshifts were in the range 0.001 to 0.3, with a mean of 0.06 and median of 0.05.

About three quarters of the SNe in the final sample were dicovered by the KAIT/LOSS SN survey, the SDSS SN survey and amateur astronomers in almost equal proportions. The rest were discovered by various surveys including the Nearby SN Factory, among others.

## 3   ANALYSIS

We use elliptical projected radial coordinates and model the surface brightness profiles of the early–type galaxies in our sample as (Sérsic 1968):

$$I(r) \equiv I_e \ \exp\left\{-b_n\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]\right\}, \qquad (1)$$

where $n$ is known as the Sérsic index (normally assumed to be four in early–type galaxies) and by definition half of the light comes from $r < r_e$, with $I_e \equiv I(r_e)$. These requirements define $b_n$, approximately $2n - 1/3$.

Now, using the change of variable $u \equiv b_n\left(\frac{r}{r_e}\right)^{1/n}$ one can show that the probability density per unit variable $u$ of a photon coming at a radius $r = r_e(u/b_n)^n$ is:

$$f_u(u) = \frac{u^{2n-1}e^{-u}}{\int_0^\infty t^{2n-1}e^{-t}dt} = \frac{u^{2n-1}}{\Gamma(2n)}e^{-u}, \qquad (2)$$

where $\Gamma(u) \equiv \int_0^\infty t^{u-1}e^{-t}dt$. This allows one to define an equivalent SN Ia rate surface magnitude brightness:

$$\mu_{Ia} \equiv -2.5 \ \ln\left(\frac{f_u(u) \ \Gamma(2n)}{u^{2n-1}}\right) = 2.5 \ b_n\left(\frac{r}{r_e}\right)^{1/n}, \qquad (3)$$

which, for a given $n$, should have the same slope of the log of the true surface brightness in $(r/r_e)^{1/n}$ space, but differ by a constant.

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[1]  See: http://www.cfa.harvard.edu/iau/lists/Supernovae.html

Thus, the cumulative probability distribution per unit variable $u$ that a photon comes from inside a region of radius $r = r_e(u/b_n)^n$ is:

$$F_u(u) = P(2n, \ u), \qquad (4)$$

where $P(a, \ u)$ is the regularised incomplete Gamma function defined as $P(a, \ u) \equiv \int_0^u t^{a-1}e^{-t}dt \ / \ \Gamma(a)$.

With the distribution of normalised distances of observed SNe Ia it is possible to test whether the SN Ia rate is proportional to the surface brightness intensity in early–type galaxies.

## 3.1 Systematic effects

Since core collapse SNe are very rare in early-type hosts, SN type misclassification is unlikely. However, early–type galaxies have extended radial profiles that easily overlap with other galaxies in the line of sight, making host galaxy identification problems important at large radii. Moreover, several effects will occur at small radii: different point–spread functions, deviations from the Sérsic profile close to galaxy cores, astrometric errors between SDSS and SN discovery coordinates, or the Shaw effect (Shaw 1979), i.e. undetected SNe near the core of galaxies due to the saturation of old photographic plates. To minimise these systematic errors we limit our sample to SNe with intermediate radii.

SDSS positions are accurate to $0.1''$ (Pier et al. 2003) and only 15% of the SNe in our sample were discovered before 2000, which means that astrometric problems or the Shaw effect are unlikely to be significant. We define a minimum SN distance of 0.2 half–light radii, since this central zone is well resolved in more than 80% of the images. For the smallest allowed half–light radii this corresponds to about five times the SDSS astrometric accuracy, but about two times the SDSS resolution. We also define an arbitrary maximum distance of four half-light radii, which is the radius at which approximately 85% of the light of the galaxy is contained in a de Vaucouleurs profile. The resulting mean and median SN distances from the galaxy cores were $18.2''$ and $9.6''$, about 45 and 24 pixels, or 13 and 7 times de resolution, respectively.

Thus, we limit our sample to SNe with $0.2 < r/r_e < 4$. When more than one host candidate met these requirements we arbitrarily chose the one closer to the SNe. This could bias our results to a centrally concentrated distribution, but dim host galaxies that are not seen in SDSS images could have the opposite effect.

In Fig. 1 we plot the equivalent of the surface brightness profile using type Ia SNe and assuming a de Vaucouleurs law with the restricted normalised distances defined above. As a first approximation it shows that SNe Ia follow their early–type host light profiles. Other authors have studied the radial distribution of type Ia SNe, but not using half–light radii normalised distances (Ivanov, Hamuy, & Pinto 2000; Bartunov, Tsvetkov, & Pavlyuk 2007). Recently, Totani et al. (2008) have also used half–light radii normalised distances, but with photometrically typed SNe Ia at high redshift and with a much lower relative resolution.
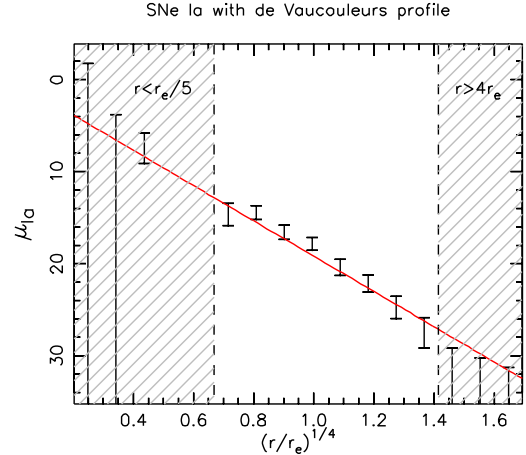
**Figure 1.** Observed (error bars) values of $\mu_{Ia}$, defined by eq. (3), vs the expected values (line) if SNe Ia follow a de Vaucouleurs law in early–type galaxies. The binning is robust at intermediate radii, with 5 or more elements in more than 80% of the bins.

## 3.2 Goodness of Fit test

To quantitatively test the hypothesis that SNe Ia follow their early–type hosts light profiles in this limited sample we normalise the cumulative probability distribution in equation (4), so that $b_n \ 0.2^{1/n} < u < b_n \ 4^{1/n}$, and contrast it with the observed cumulative distribution using a Kolmogorov-Smirnov (KS) goodness of fit test. We conclude that for this restricted region the SN Ia rate is statistically consistent with a de Vaucouleurs profile (see Fig. 2).

However, it is known that early–type galaxies light profiles have a continuous distribution of Sérsic indices connecting dwarf to giant ellipticals, increasing from approximately $n = 2$ to $n = 6$ (Graham & Guzmán 2003). We have included a variable Sérsic index in our fitting procedure and found that the best–fitting Sérsic indices are distributed in approximately the same range, but have a slight preference for lower values, with an average of 3.4 and a median of 3.3. This distribution might be a result of the way SNe Ia have historically been discovered, which in many cases depends on pre–selected galaxy samples.

To allow for this diversity to be included in our analysis we use a new change of variable suggested by eq. (4), namely $v \equiv P(2n, u)$, or the fraction of the integrated light of the galaxy at the position of the SNe if the profile was well described by equation (1). The new probability density and cumulative probability density will be simply:

$$f_v(v) = 1 \qquad \text{and} \qquad F_v(v) = v, \qquad (5)$$

which are independent of $n$. This allows us to compare all galaxies irrespective of their Sérsic indices.

Hence, after finding the best–fitting values of $n$ for each individual galaxy we set a cut for the SN sample based on the new variable $v$ rather than $u$. Given that the half–light radii resulting from the Sérsic profile fitting were on average smaller, we limit our sample to SNe within $0.2 < u < 0.85$, equivalent to $0.3 < r/r_e < 4$ for the average Sérsic index. We also select galaxies were the best-fitting Sérsic indices were in the expected range $2 < n < 6$. The distribution of the variable $v$ contrasted to $F_v(v)$ is in Fig. 2.
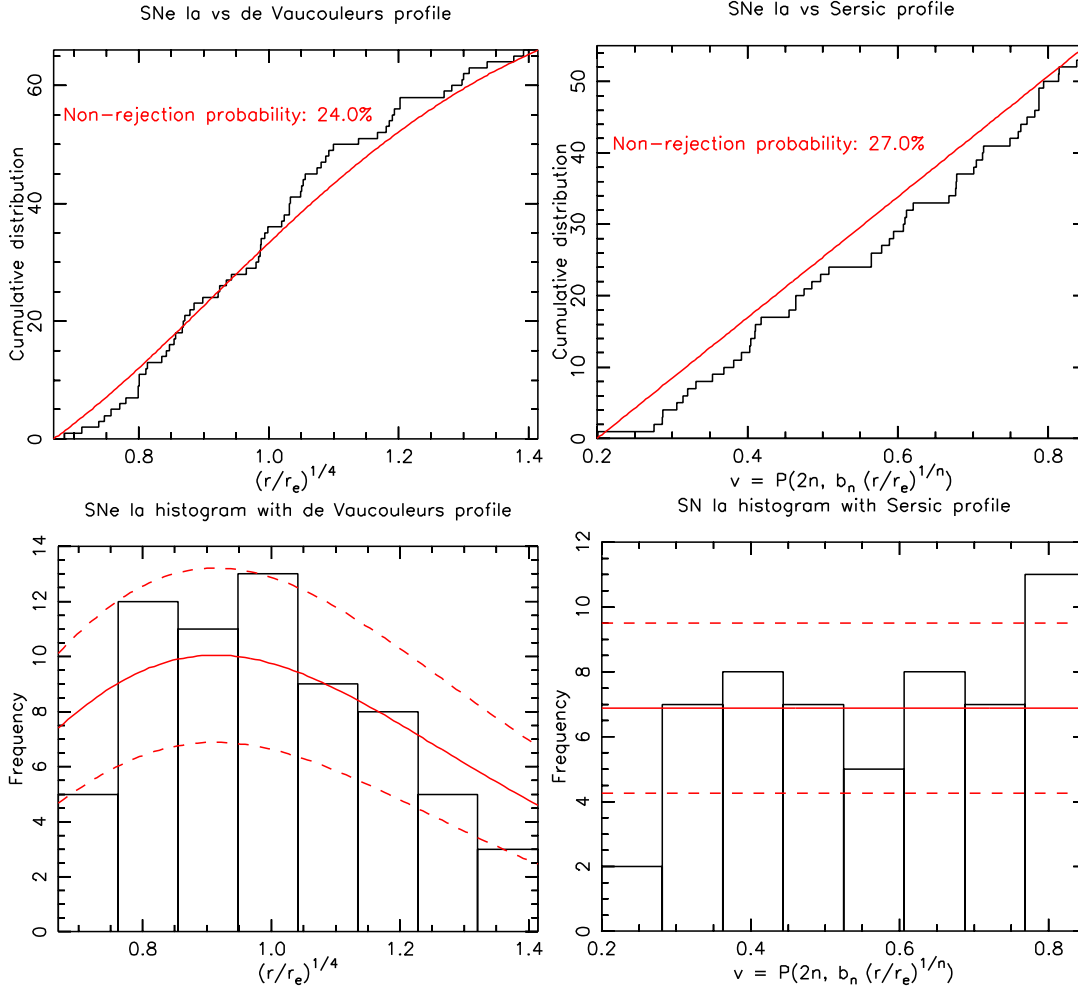
**Figure 2.** Kolmogorov Smirnov tests of the cumulative distribution of SNe Ia (top) and SN Ia histograms (bottom) assuming a de Vaucouleurs profile (left) or a Sérsic profile (right) and the predicted distributions. The data was binned so that more than 80% of the bins would have at least 5 elements. Note that different selection criteria led to different sample sizes.

## 4    CONCLUSIONS AND DISCUSSION

We have found that there is no statistically significant difference between the radial dependence of the SN Ia rate in morphologically selected early–type galaxies and their host surface brightness profiles at intermediate radii. The probabilities of not rejecting the hypotheses that SNe Ia follow a de Vaucouleurs or Sérsic profile is 24.0% and 27.0%.

In this work we use host half–light radii ($r_e$) normalised distances, obtained after fitting de Vaucouleurs or Sérsic profiles on $r$ band SDSS images, and quantified any deviations from a de Vaucouleurs or Sérsic profile at intermediate radii. Intermediate radii are defined in Section 3.

The main implications of this work is that the time delay of type Ia SNe in early–type galaxies should be of the order of the age of their host galaxies, or several Gyr. This assumes that young stellar populations of early–type galaxies do not follow the light distribution of their hosts, which is supported by recent observations of central molecular disks and high–resolution SAURON H$\beta$ maps and stellar populations reconstructions, showing that when young ($\lesssim 1$ Gyr) stellar populations are present, they are mainly in the central regions of their hosts. Even after including small radii

in our sample we did not see an excess of the SN Ia rate in the central parts of early–type galaxies, but given all the possible systematic errors of our method we cannot conclude if there is any real deficit.

Our result does not exclude either the SD or DD scenarios in a picture of multiple progenitor scenarios, but confirms the idea that very young SN Ia progenitor scenarios are probably not dominant in early–type galaxies. They rather indicate that long time delays of several Gyrs for SNe Ia in early–type galaxies are dominant.

Interestingly, early-type galaxies are known to exhibit radial gradients in metallicity, but not in age or $\alpha$-enhancement (Saglia et al. 2000; Mehlert et al. 2003; Wu et al. 2005). The metallicity gradients range all the way to the outer parts of early-type galaxies, beyond two effective radii (Méndez et al. 2005). Given this, our result also suggests that within the metallicity range exhibited by massive early-type galaxies, the SN Ia rate appears not to be strongly affected by metallicity, which hints that long time–delay SN Ia progenitor scenarios may not have a very strong metallicity dependence. Note that a significant dependence has been predicted for metallicities below solar (see Kobayashi et al. 1998; Meng, Chen, & Han 2008).

If the metallicity gradients and surface brightness profiles are relics of the process of galaxy formation in early–type galaxies, our result would suggest that the progenitors of long time–delay SN Ia are as old as their host galaxies.

Future studies of the radial distribution of sub–classes of SNe Ia, e.g. SN1991bg and SN1991T–like events, should provide further insights into whether there are multiple progenitor scenarios (see e.g. Scannapieco & Bildsten 2005).

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